

Pulsed Laser Deposition of YBCO for High I_c Coated Conductor Development

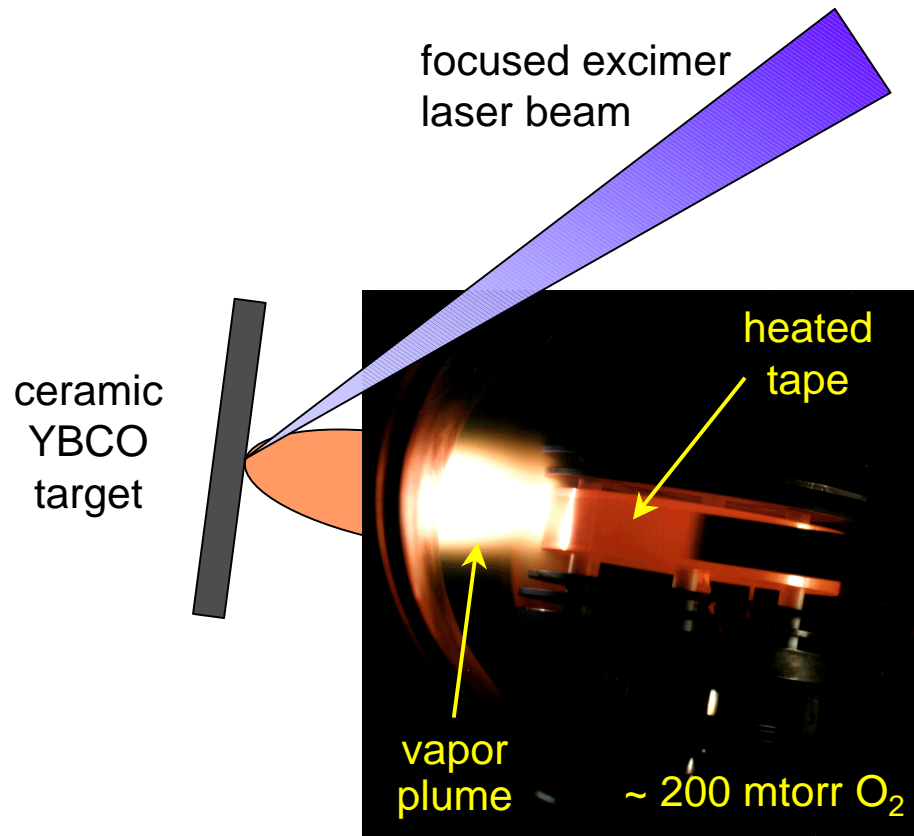
Steve Foltyn, Paul Arendt, Quanxi Jia,
Haiyan Wang, Jim Smith, Yuan Li

*Superconductivity Technology Center
Los Alamos National Laboratory*

PLD basics

Unique aspects of PLD:

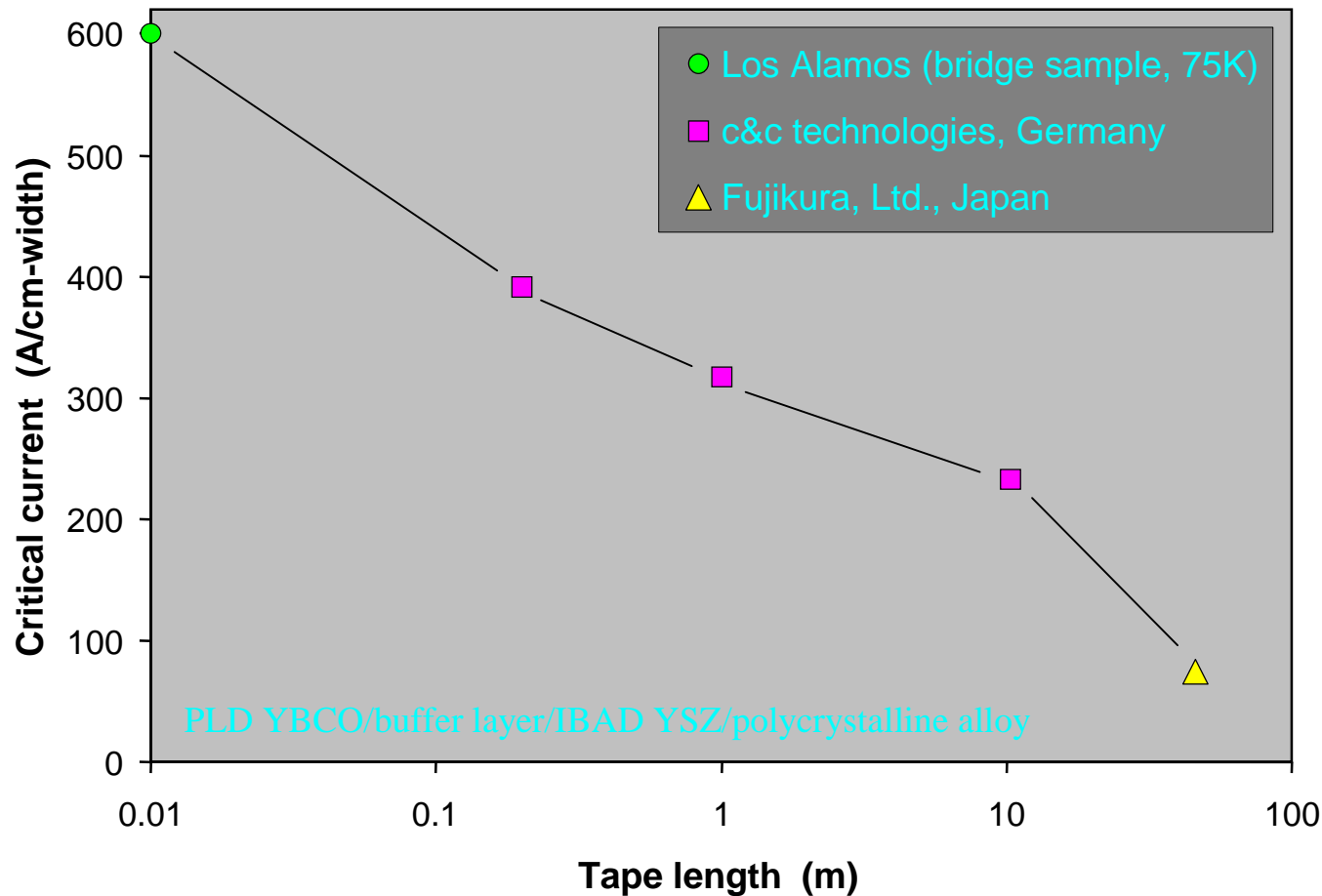
- Energy deposited in the target surface is $\sim 1 \text{ MJ/cm}^2$ in a 25 ns pulse.
- Deposition consists of short pulses of extremely high rate, separated by relatively long periods with no film growth.
- Optimum YBCO growth requires a balance between laser energy, target-substrate distance, and background pressure.



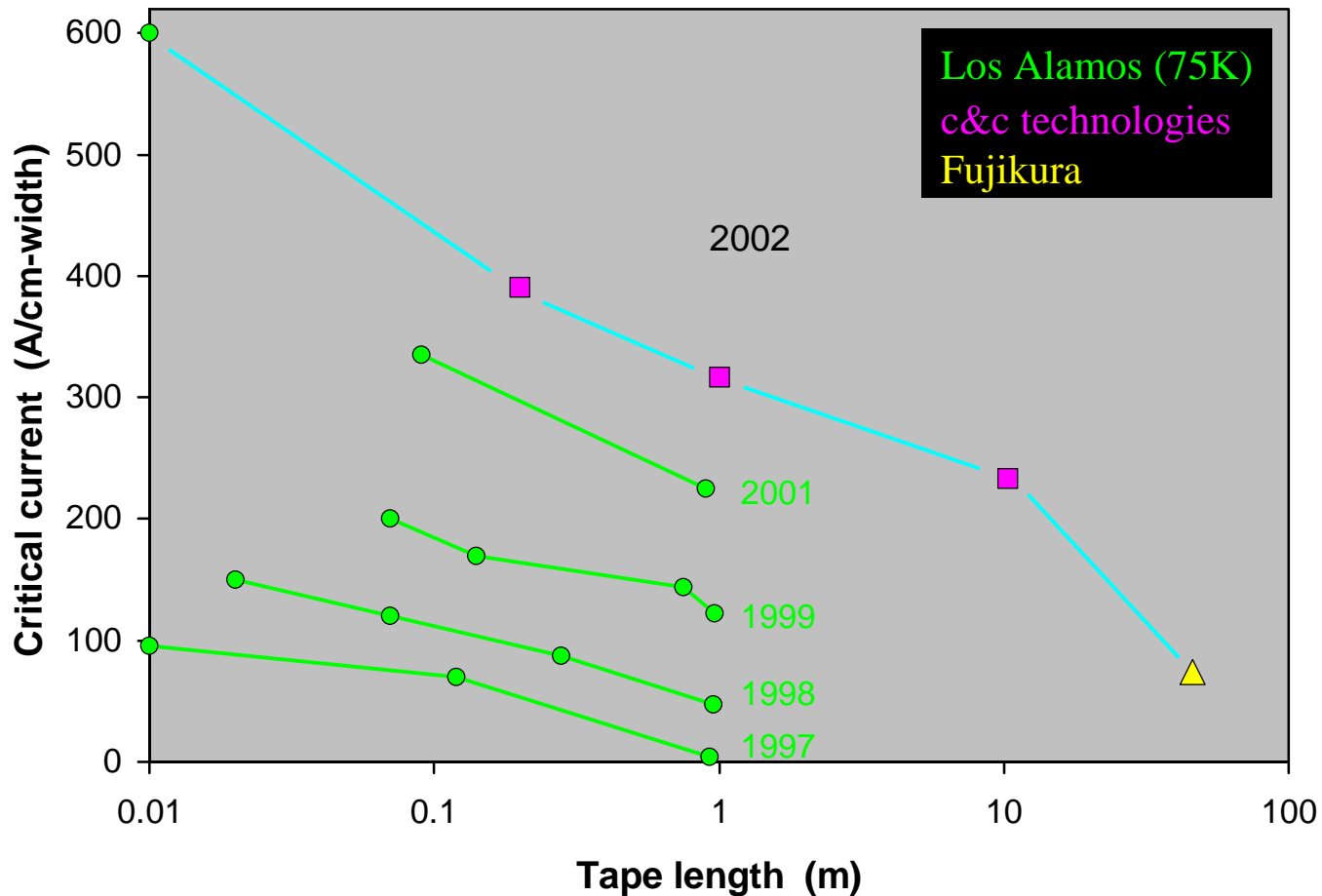
Contributions of PLD to coated conductor development -- highlights

- 1991-2 – First coated conductors (textured YBCO on metal) demonstrated.
- 1993 – First thick YBCO with high J_c ($\sim 1 \text{ MA/cm}^2$ at $> 6 \mu\text{m}$ thickness – single-crystal substrate).
- 1995 – First coated conductor with $I_c = 200 \text{ A}$ (1 cm wide).
- 1999 – First continuously-processed meter with $I_c > 100 \text{ A}$ (1 cm wide)
- 2000 – First coated conductor samples with $I_c > 500 \text{ A/cm-width}$ ($200 \mu\text{m} \times 5 \text{ mm}$ bridges).
- today – Three companies worldwide are actively investigating commercial production of coated conductors with PLD.

PLD-YBCO coated conductors have the highest critical current values at all length scales



PLD-based conductors have steadily improved



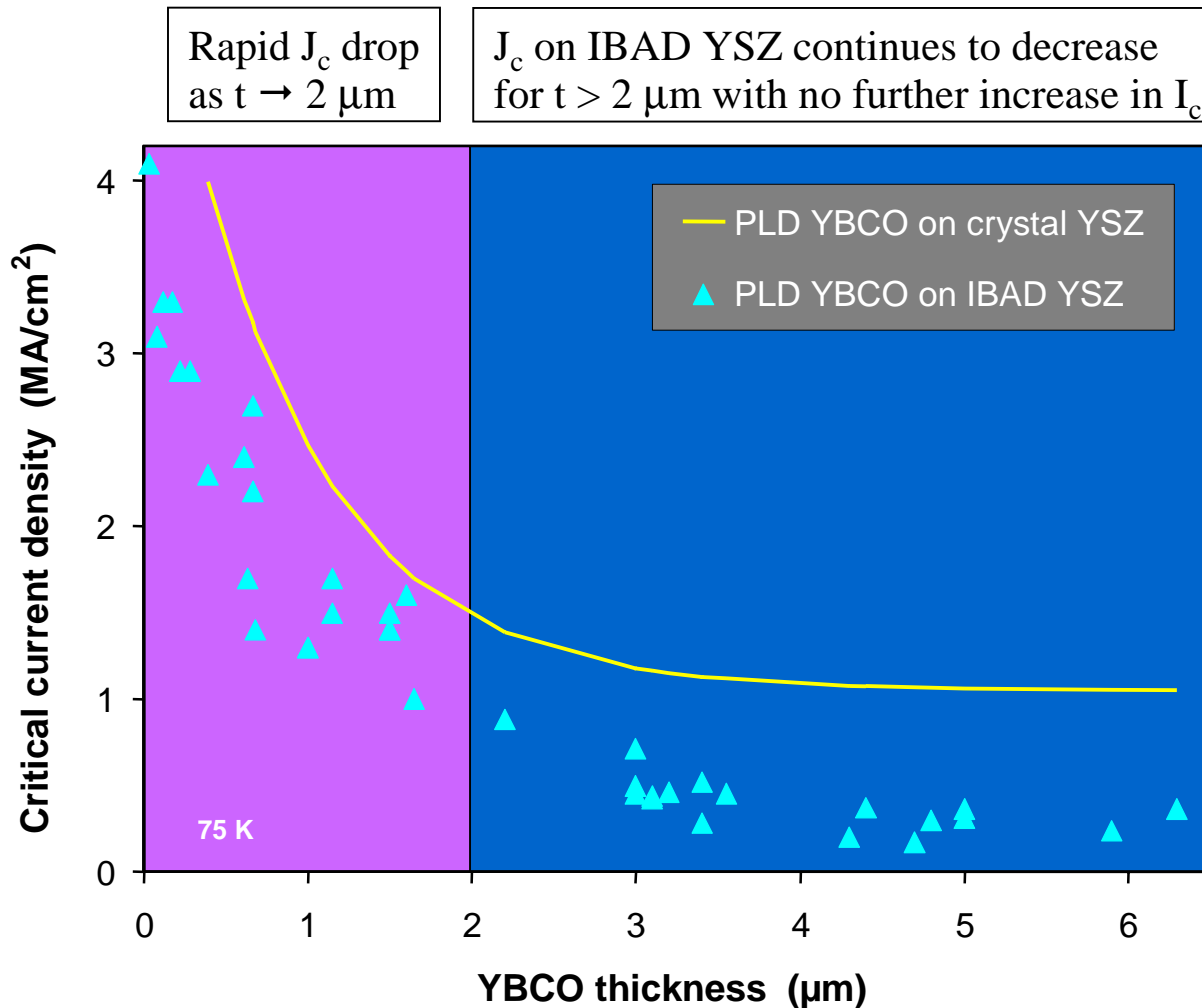
Although the deposition area is small, PLD is capable of processing high- I_c tape at high line speed

- With a 200 W laser, we produced a meter of 1 μm thick x 1 cm wide YBCO in 4 minutes (15 m/h).
- We were able to maintain high J_c at these high deposition rates -- I_c s of 100 - 200 A are readily achievable at this rate.
- Since this demonstration, a 300 W laser capable of 24/7 operation has come on the market.
- The demonstrated rate extrapolates to ~ 200 km/y for a single 300 W laser running 24/7.
- In the demonstration, only about half of the laser power was getting into the chamber, and less than half of the vapor was collected on tape – efficiency can be improved in both areas.

Conclusions (PLD)

- PLD is a fast, simple, and reliable way to deposit YBCO and/or essentially any buffer layer needed for coated conductors.
- PLD has led the way in coated conductor development and continues to produce tapes with the best performance.
- Three companies are actively investigating PLD as a route to commercial production of coated conductors.

The “thick film problem” we previously reported for IBAD YSZ-based coated conductors has two parts



Process modifications solve the $t > 2 \mu\text{m}$ problem; I_c values of 300 – 400 A/cm-width on IBAD YSZ are routinely achieved

Successful process modifications include:

- Multilayers (first reported at 2000 Peer Review)
- Certain mixtures of RE123 materials
- High *instantaneous* rate PLD (~ 4 A/shot)

What is the source of the problem at $t > 2 \mu\text{m}$?

Hypothesis – J_c continues to drop at $t > 2 \mu\text{m}$ because of porosity (i.e. poor connectivity) that evolves in thicker YBCO.

Evidence

- SEM cross-sections show onset of porosity at $\sim 1.5 \mu\text{m}$
- Thinning experiments show negligible J_c above $\sim 1.5 \mu\text{m}$
- When porosity is reduced by process modification, high J_c is observed throughout thick films.

What is the source of the problem at $t > 2 \mu\text{m}$? (cont.)

Hypothesis – Porosity results from cumulative roughening of the growing YBCO surface, which reduces the mobility of arriving vapor species.

Evidence

- SEM plan views show greater roughness for thicker YBCO.
- Process modifications that yield high J_c for thick films also yield smoother surfaces
- One process modification – high instantaneous rate – produces more energetic vapor at the growing surface, thereby enhancing mobility.

Question – How do multilayers or RE mixtures improve mobility and/or reduce roughness and porosity?

Are there other possible solutions?

Hypothesis – If insufficient mobility is the issue, other processes such as low *average* rate PLD, or ex-situ YBCO growth may exhibit less porosity due to longer time-at-temperature.

Evidence – Oak Ridge?

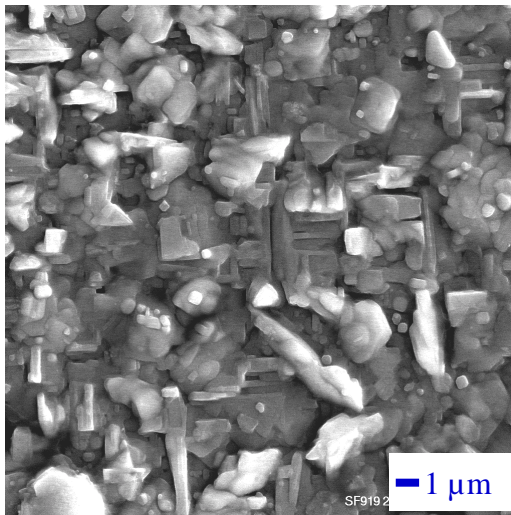
Hypothesis – IBAD YSZ is rough at the surface – starting with a smoother substrate/buffer combination may reduce porosity or delay its onset.

Evidence

- Original films on single-crystal substrates (with very smooth surfaces) had no porosity and had high J_c throughout YBCO thicknesses of over 6 microns.
- A recent result for thick YBCO on IBAD MgO (which is much smoother than IBAD YSZ) also exhibits high J_c , a smooth surface, and minimal porosity ...

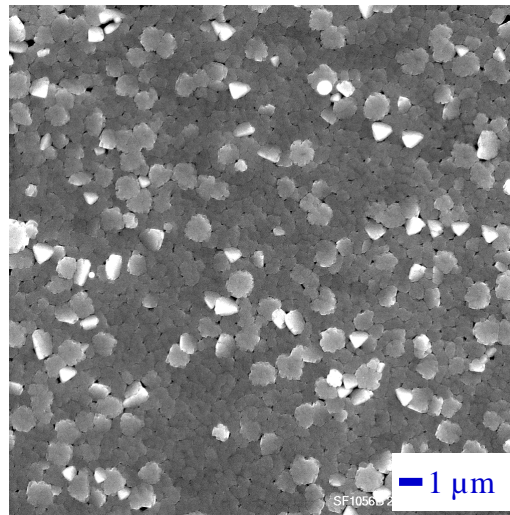
On IBAD MgO/SrRuO₃ , which is smoother than IBAD YSZ,
high I_c YBCO can be deposited with no process modifications

3.0 μm YBCO on IBAD
YSZ -- standard process



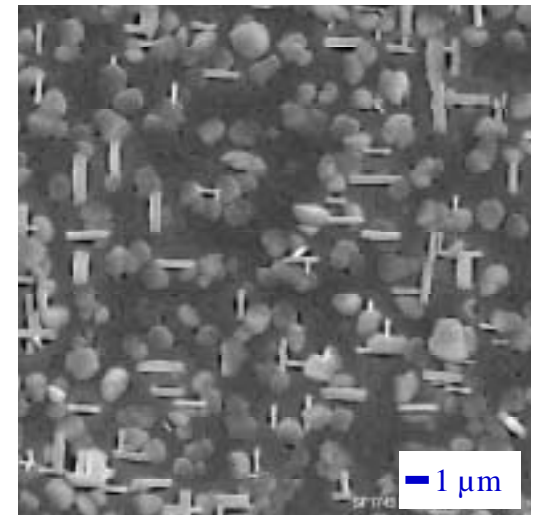
$J_c = 0.6 \text{ MA/cm}^2$
 $I_c = 180 \text{ A/cm-width}$

3.7 μm Y/Sm multilayer
on IBAD YSZ



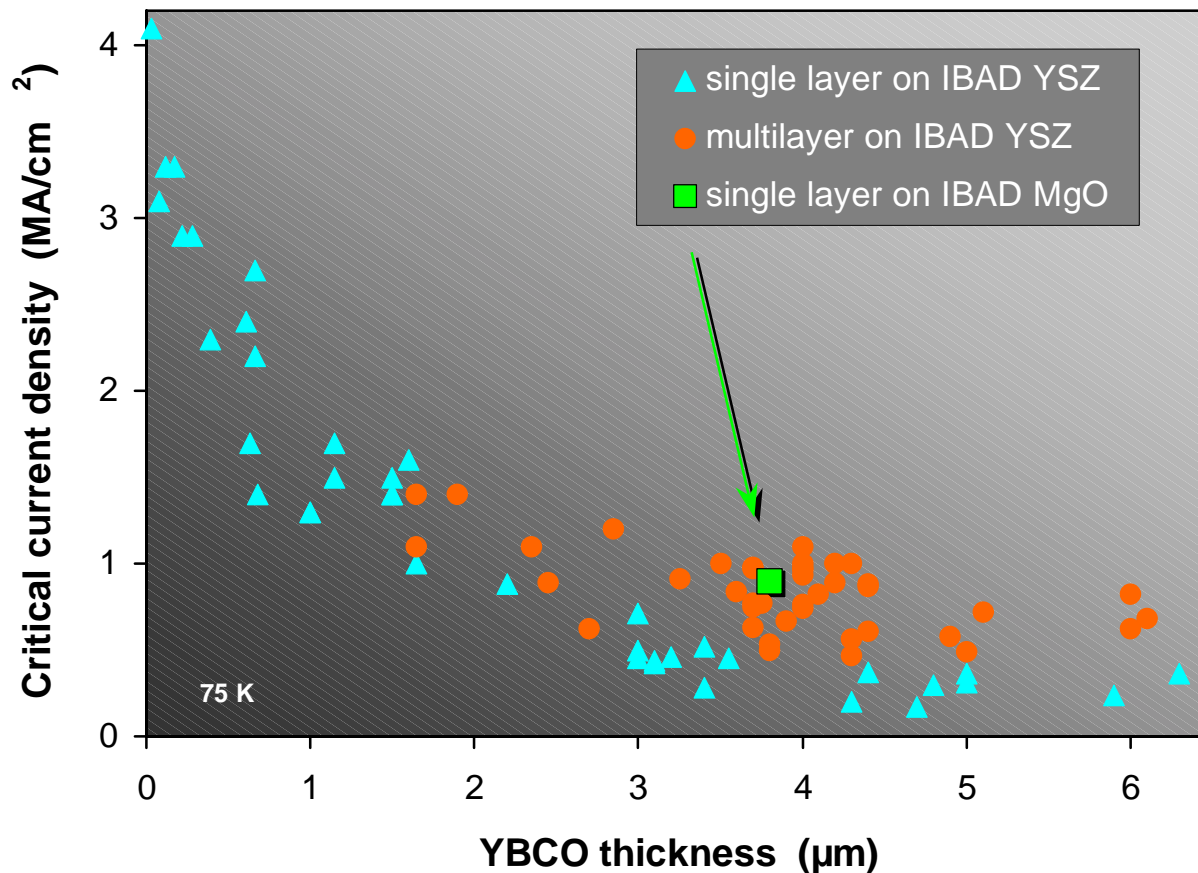
$J_c = 1.1 \text{ MA/cm}^2$
 $I_c = 405 \text{ A/cm-width}$

3.8 μm YBCO on IBAD
MgO -- standard process



$J_c = 0.9 \text{ MA/cm}^2$
 $I_c = 340 \text{ A/cm-width}$

“Standard” YBCO on IBAD MgO is comparable to our best multilayer coatings on IBAD YSZ



Conclusions (Thick films)

- The problem that keeps I_c from increasing for YBCO thicknesses beyond $2\text{ }\mu\text{m}$ is basically resolved:
 - \Rightarrow It may be limited to rough starting surfaces (e.g. IBAD YSZ)
 - \Rightarrow There are several ways to solve the problem
 - \Rightarrow Very thick YBCO may be commercially impractical
- The more interesting -- and economically significant -- issue is improving J_c for thinner films ...

... and this is where we will concentrate our future efforts

